Status of FLASH and European XFEL and recent FEL developments at FLASH

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For FLASH and European XFEL Team

Innovative FEL developments using variable gap undulator at FLASH2:

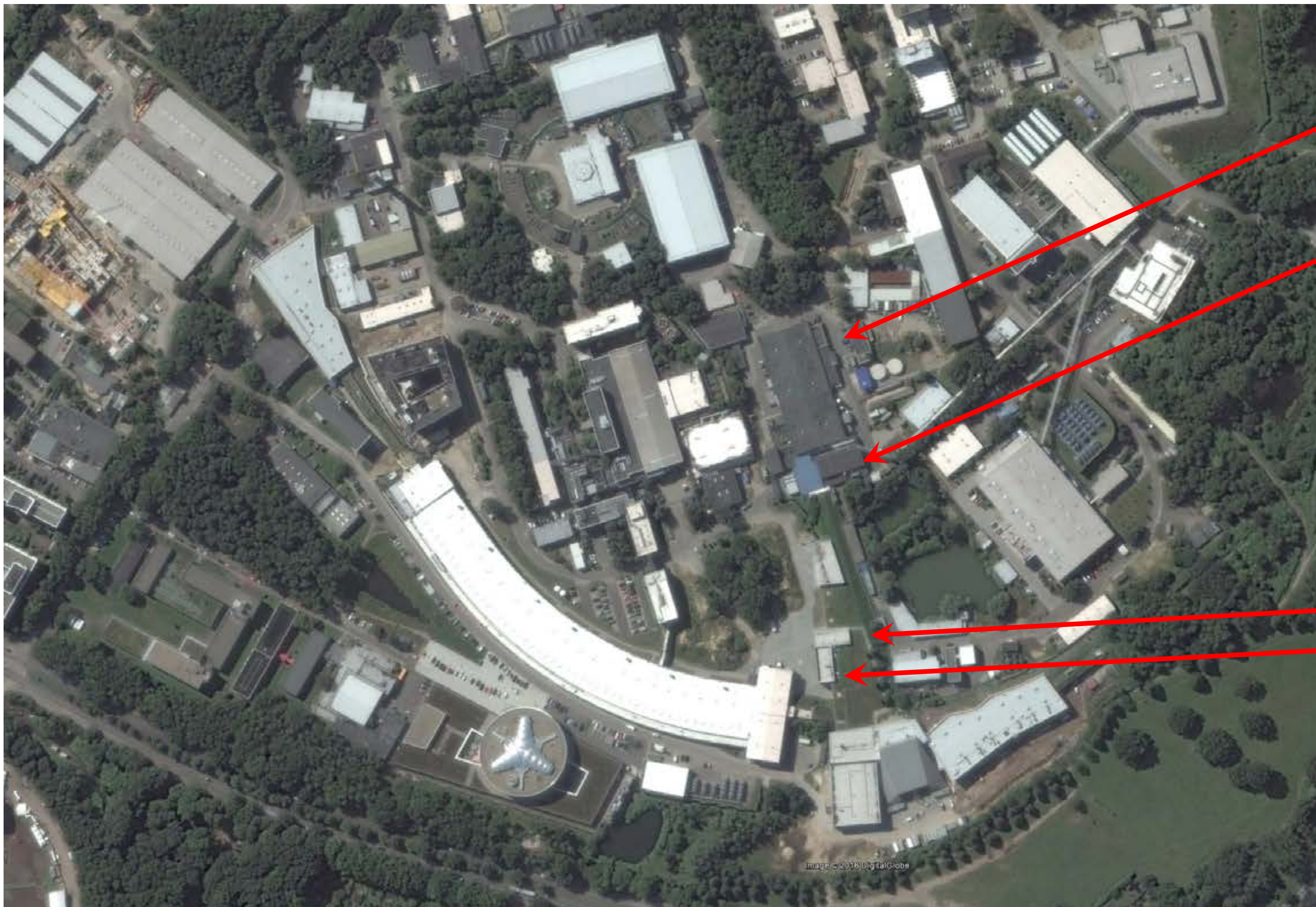
- Frequency doubler.
- Reverse undulator tapering.
- Harmonic lasing.
- Harmonic Lasing Self Seeded FEL (HLSS).
- Post saturation undulator tapering.

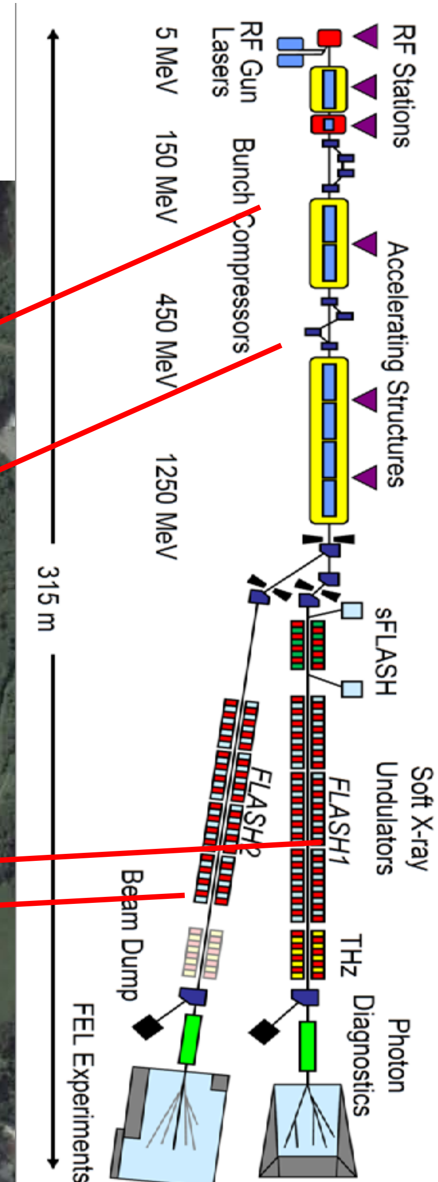
DESY areal view in August, 2015

PETRA III: East Hall, Max von Laue Hall (left), Nord Hall (left)

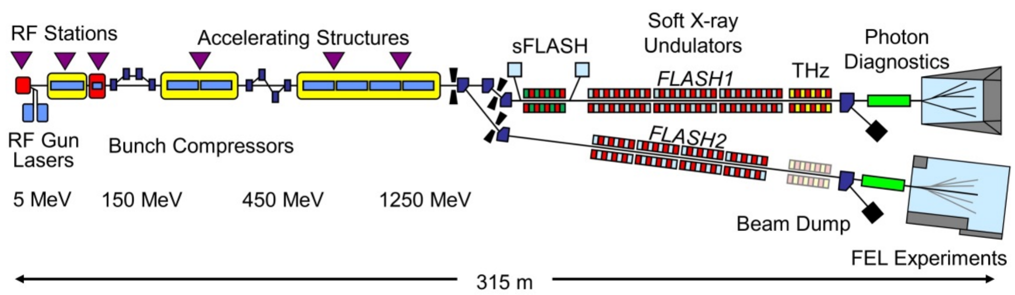
FLASH: 1.25 GeV SC linac, FLASH and FLASH2 experimental hall (center)

European XFEL: AMTF, cryogenic plant and injector (top-right)





FLASH facility in 2016



Linac: SRF burst, 1 msec x 10 Hz

Energy [GeV] 0.5-1.25

Length [m] 315

Undulators:

	Period	Length	
FLASH1:	2.73 cm	27 m (6 x 4.5 m modules)	fixed gap
FLASH2:	3.14 cm	30 m (12 x 2 m modules)	variable gap

Radiation:

Wavelength [nm] 4.1-55 (FLASH1), 3.1-8.x (FLASH2)

Up to 0.8 W average radiation power

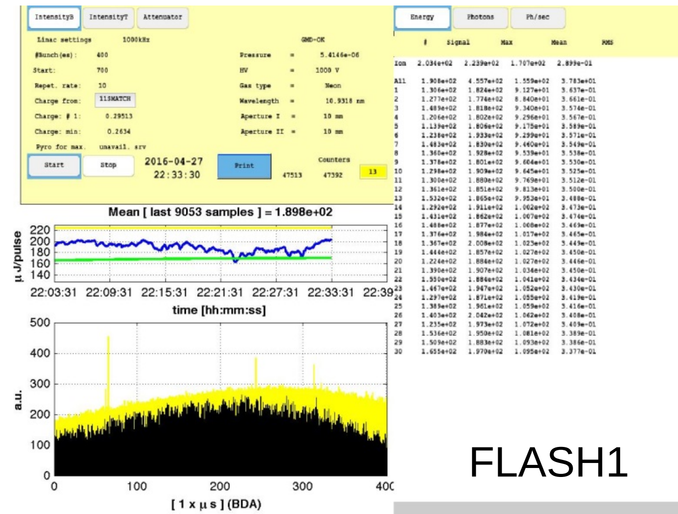
Up to 1 mJ average radiation pulse energy

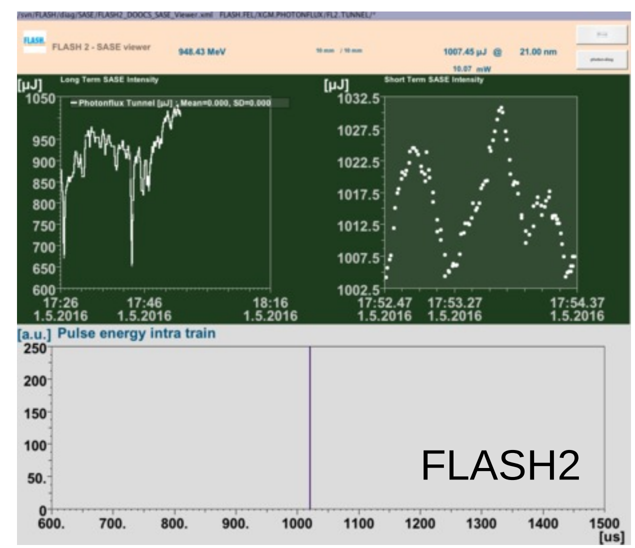
A few 10 fs to a few 100 fs pulse duration

A few GW peak radiation power

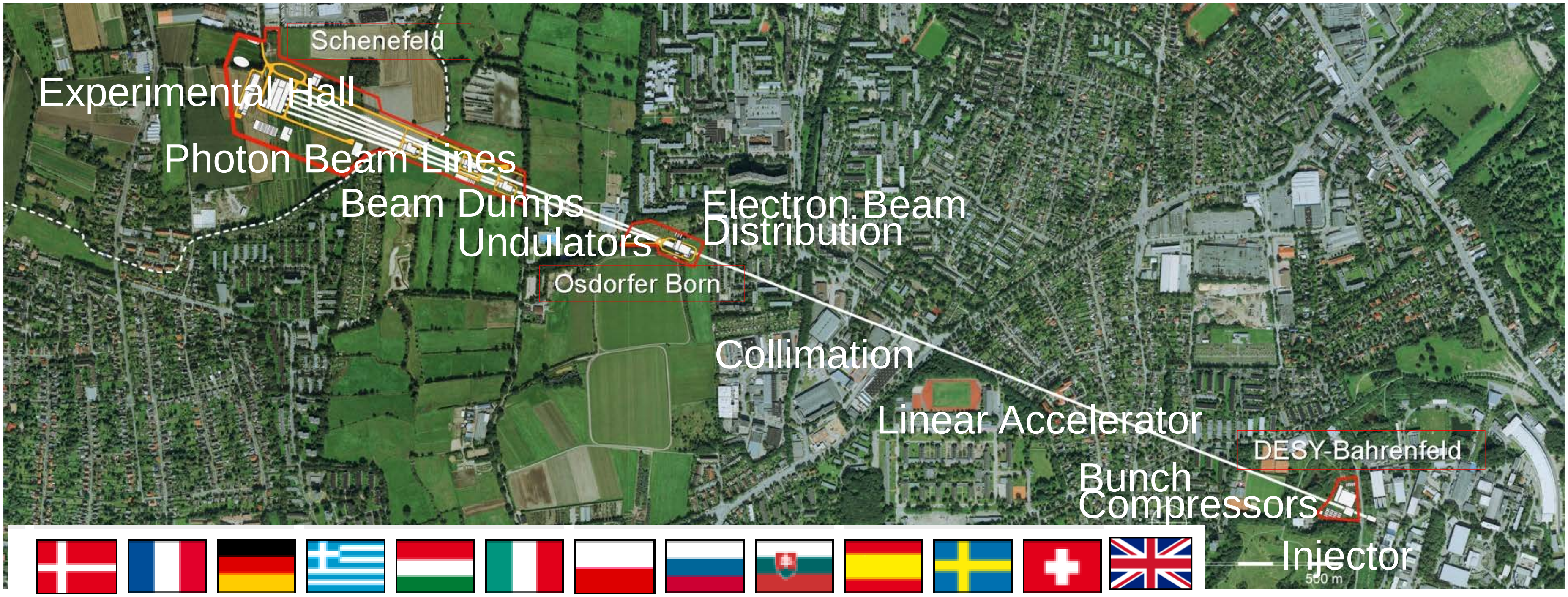
Up to 5000 pulses per second

Simultaneous operation of two FEL beamlines





European XFEL



1997: Conceptual Design of 500 GeV e+e- Linear Collider with Integrated X-ray Facility.

2001: TESLA Technical Design Report.

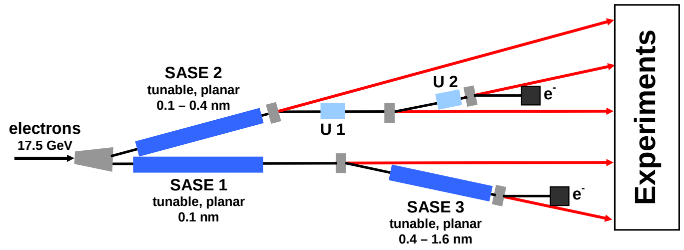
2002: TESLA XFEL: First stage of the X-ray laser laboratory - Technical design report.

2003: Decision of the German Federal Ministry of Education and Research: The X-ray laser laboratory is to be realized as a European project at DESY, and Germany will bear approximately half of the costs because of the advantage of location

2006: The European X-Ray Free-Electron Laser: Technical design report.

2009: Start of the construction.

European XFEL: Multi-user facility
6 instruments in baseline option



Undulators at the European XFEL

	Units	SASE1 SASE2	SASE3
Period length	cm	4	6.8
Minimum gap	cm	1	1
Maximum peak field	T	1.2	1.7
Total magnetic length	m	175	105

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SASE1/2: gap = 10 mm ... 20 mm   K = 3.9 ... 1.65
SASE3:   gap = 10 mm ... 25 mm   K = 9 ... 4.08
Tunability range at fixed energy for SASE1/2:     3.7
Tunability range at fixed energy for SASE3:       4.5
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E [GeV]	SASE3	SASE1/2
Photon energy range [keV]:		
8.5	0.24- 1.08	1.99- 7.27
12.0	0.48- 2.16	3.97-14.48
14.0	0.66- 2.94	5.41-19.71
17.5	1.03- 4.59	8.45-30.80
Photon wavelength range [nm]		
8.50	1.15- 5.10	0.171-0.622
12.00	0.57- 2.56	0.086-0.312
14.00	0.42- 1.88	0.063-0.229
17.50	0.27- 1.20	0.040-0.147

SPB: Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters, and Biomolecules

- Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells.

MID: Materials Imaging & Dynamics

- Structure determination of nano-devices and dynamics at the nanoscale.

FXE: Femtosecond X-ray Experiments

- Time-resolved investigations of the dynamics of solids, liquids, gases

HED: High Energy Density Matter

- Investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas

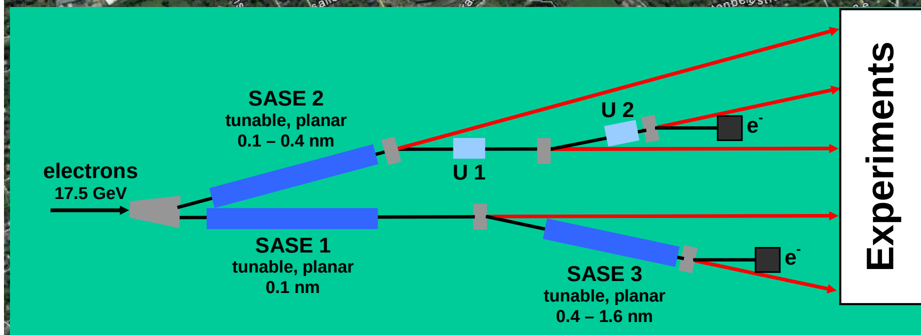
SQS: Small Quantum Systems

- Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena

SCS: Soft x-ray Coherent Scattering/Spectroscopy

- Electronic and real structure, dynamics of nano-systems and of non-reproducible biological objects

Status of the European XFEL, October 2016



Buildings, tunnels, and infrastructure are ready.

Linac is assembled.

SASE1 undulator is installed.

Commissioning of the facility started.

Scientific instruments are under preparation.

First user experiments are expected in 2017.

European XFEL: 17.5 GeV, 0.05 nm, 3.5 km

FLASH: 1.25 GeV, 3.1 nm, 0.3 km

Innovative FEL developments at FLASH2

- FLASH2 undulator beamline started to serve user experiments in 2016.

- It is equipped with variable gap undulator which allows to implement novel techniques for radiation generation beyond the standard SASE FEL. As a result, properties of the radiation can be modified significantly, like increasing of the output pulse energy, improvement of the longitudinal coherence, control of polarization, extension of the wavelength range, multi-color mode of operation.

- Several innovative FEL developments using variable gap undulator have been realized at FLASH2 recently:

– Frequency doubler.
– Reverse undulator tapering.
– Harmonic lasing.
– Harmonic Lasing Self Seeded FEL (HLSS).
– Post saturation undulator tapering.

Background for advanced developments at FLASH

Harmonic lasing self-seeded FEL:

E.A. Schneidmiller, and M.V. Yurkov, Harmonic lasing in x-ray free electron lasers, Phys. Rev. ST Accel. Beams 15 (2012) 080702.

E.A. Schneidmiller, and M.V. Yurkov, Studies of harmonic lasing self-seeded FEL at FLASH2, Proc. IPAC2016, MOPOW009.

Reverse undulator tapering:

E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 16 (2013) 110702.

E.A. Schneidmiller and M.V. Yurkov, Reverse undulator tapering for polarization controls at XFELs, Proc. IPAC2016, MOPOW008

Post-saturation undulator tapering:

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, The Physics of Free Electron Lasers (Springer-Verlag, Berlin, 1999).

E.A. Schneidmiller, and M.V. Yurkov, Optimization of a high efficiency free electron laser amplifier, Phys. Rev. ST Accel. Beams 18 (2015) 030705.

E.A. Schneidmiller, and M.V. Yurkov, The universal method for optimization of undulator tapering in FEL amplifiers, Proc. SPIE Vol. 9512, 951219 (2015).

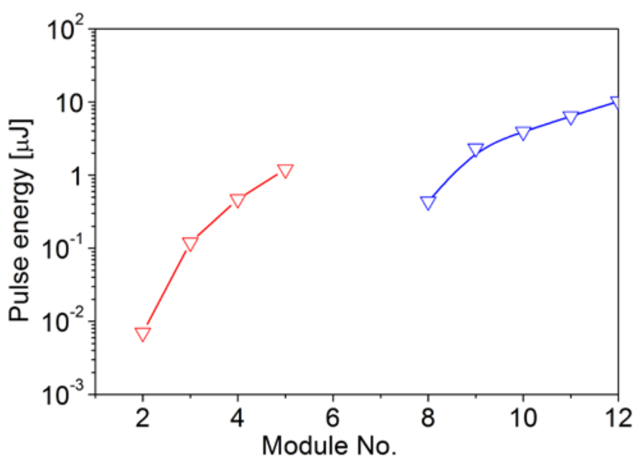
E.A. Schneidmiller and M.V. Yurkov, Application of Statistical Methods for Measurements of the Coherence Properties of the Radiation from SASE FEL, Proc. IPAC2016, MOPOW013

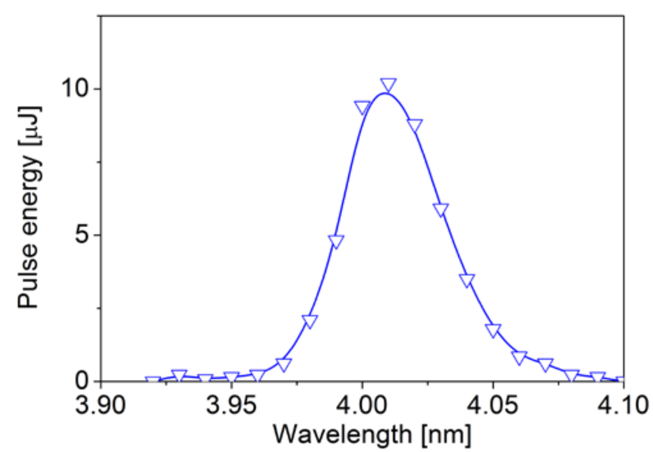
Efficient frequency doubler at FLASH2 operating in the water window:

J. Feldhaus, M. K¨orfer, T. Moeller, J. Pflueger, E.L. Saldin, E.A. Schneidmiller, M.V.Yurkov, Efficient frequency doubler for the soft X-ray SASE FEL at the TESLA Test Facility, Nucl. Instrum. and Methods A 528 (2004) 471-475.

Frequency doubler at FLASH2

- Undulator is divided in two parts. The second part is tuned to the double frequency of the first part.
- Amplification process in the first undulator part is stopped at the onset of the nonlinear regime, such that nonlinear higher harmonic bunching in the electron beam density becomes pronouncing, but the radiation level is still small to disturb the electron beam significantly.
- Modulated electron beam enters the second part of the undulator and generates radiation at the 2nd harmonic.
- Frequency doubler allows operation in a two-color mode and operation at shorter wavelengths with respect to standard SASE scheme.





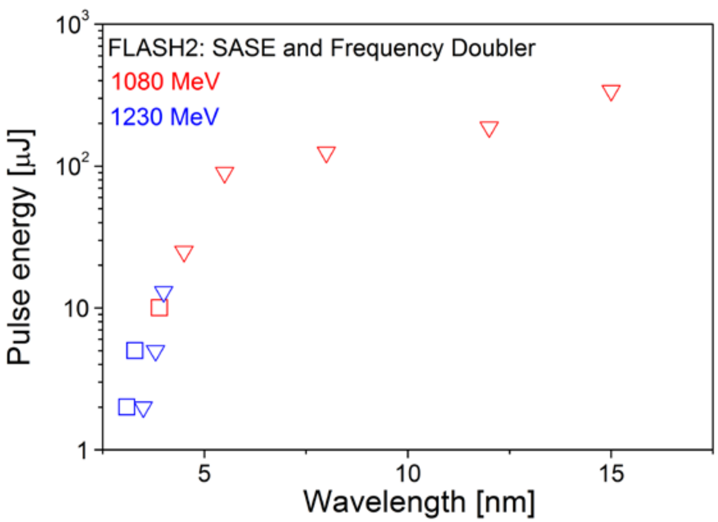
Example: frequency doubler 8 nm ➔ 4 nm.

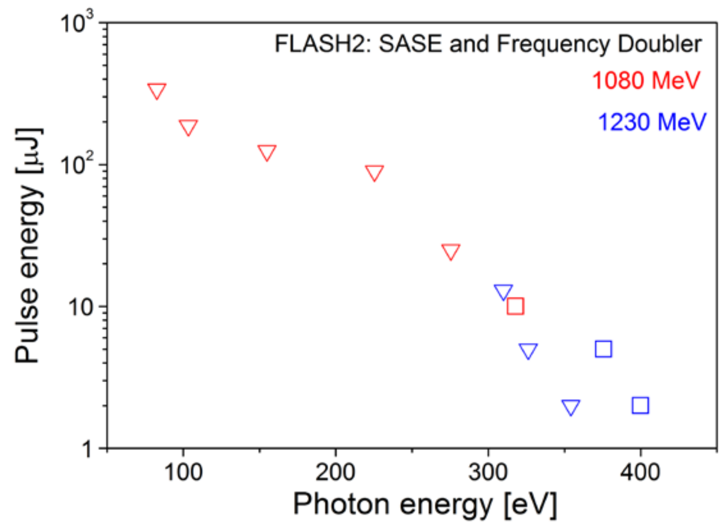
Shortest wavelengths at FLASH2

On September 15 and 23 accelerator operated with the energy of 1080 MeV and 1230 MeV. We got dedicated shifts within the FLASH studies program for the topic "Efficient frequency doubler at FLASH2 operating in the water window".

SASE configuration: 12 modules

Doubler configuration: 5u x ω + 7u x 2ω





Triangles - SASE

Squares - doubler

For "usable" range of the radiation pulse enrgies above 1 uJ, FLASH2 demonstrated operation down to 3.5 nm in the SASE mode, and down to 3.1 nm in the frequency doubler mode.

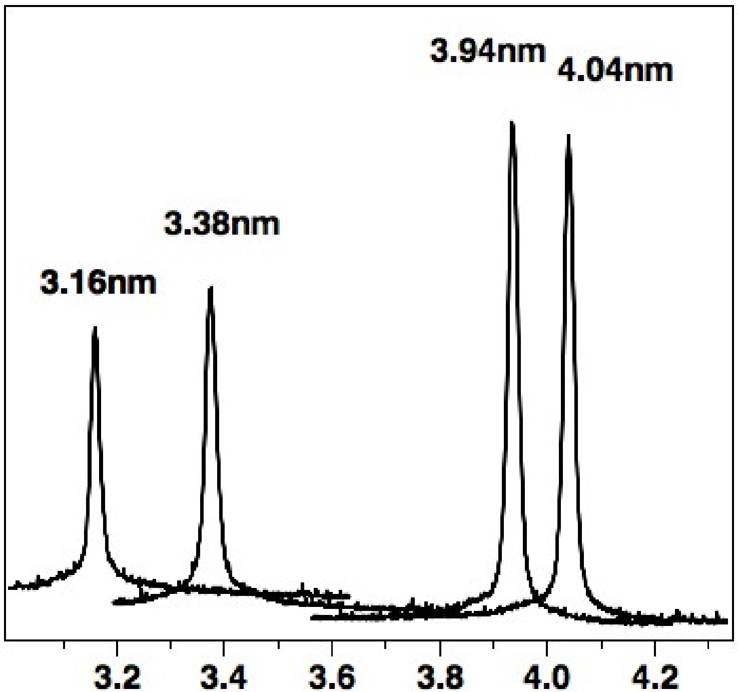
Shortest wavelengths at FLASH2

Doubler configuration: 5u x ω + 7u x 2ω

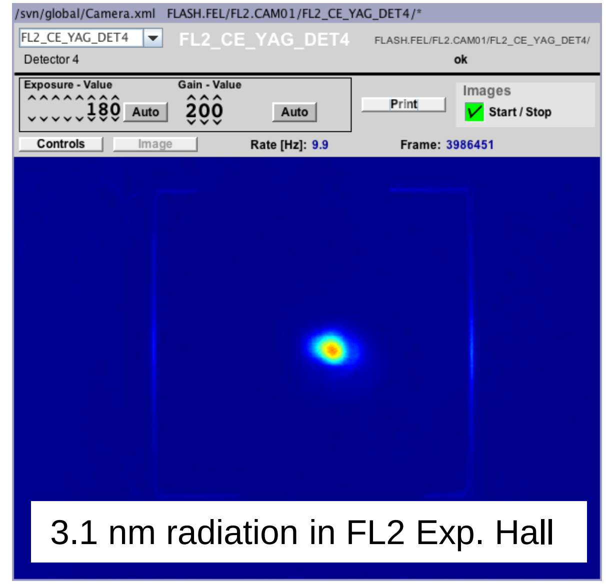
Minimum wavelength of frequency doubler:

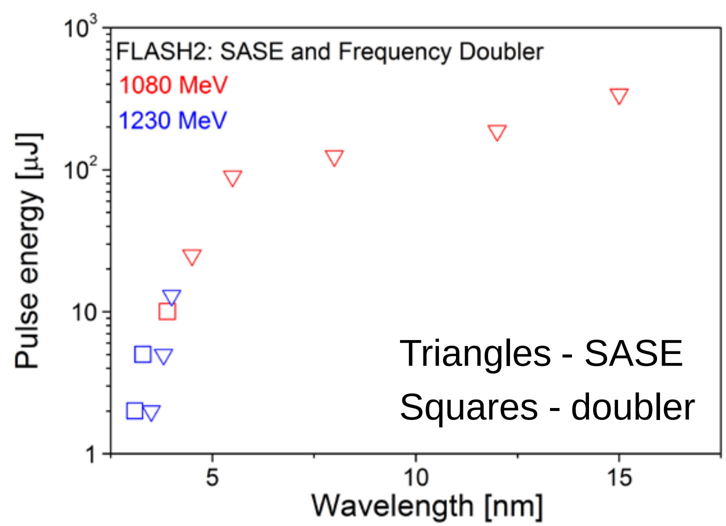
3.9 nm at 1080 MeV

3.1 nm at 1230 MeV



Courtesy to Marion Kuhlmann





Spectrum bandwith of the radiation from frequency doubler is 0.5% FWHM.

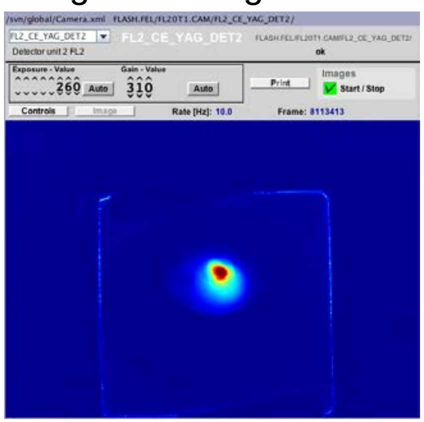
Frequency doubler: two color mode of operation

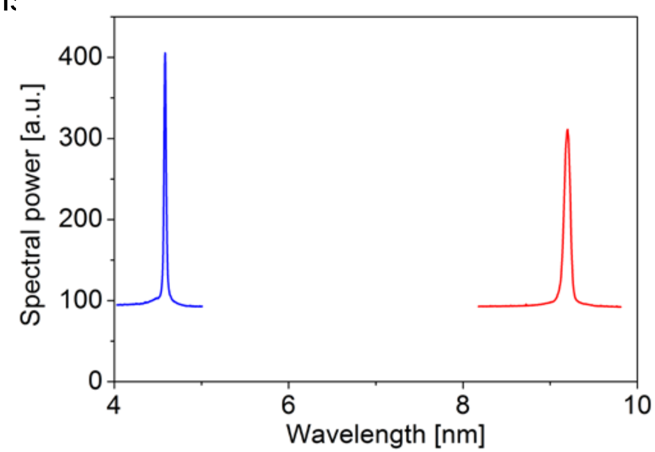
14.09.2016 22:59	Schneidmiller/Yurkov/	**Summary on frequency doubler operation at FLASH2**

FLASH2: Electron energy 1073.8 MeV, bunch charge 350 pC, 160 uJ SASE @ 9 nm, 120 uJ SASE @ 8 nm.
Doubler configuration: 5u x ω + 7u x 2ω

Successful demonstration of frequency doubler and two-color operation in the water window:
- 10 uJ at 9 nm and 10 uJ at 4.5 nm (4 uJ SASE at 4.5 nm and 12 modules)
- 3 uJ at 8 nm and 4 uJ at 4 nm (~ 0.1 uJ SASE at 4 nm and 12 modules)

Extrapolation of obtained results to the energy of 1.25 GeV: it would be possible to operate FLASH2 at the wavelength down to 3 nm. Radiation pulse energy will depend on quality of electron bunch. With good tuning 10 uJ level seems to be possible.

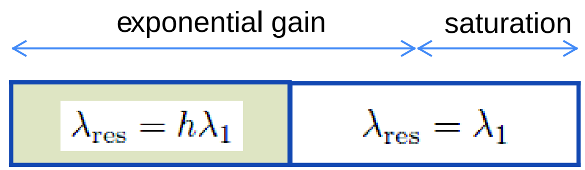




Courtesy to Marion Kuhlmann

Example: frequency doubler, two color mode of operation with 9 nm and 4.5 nm.
Small red spot is 4.5 nm (2^{nd} harmonic) radiation, 10 uJ. Larger blue spot is 9 nm radiation, 10 uJ.

Harmonic lasing self-seeding (HLSS)



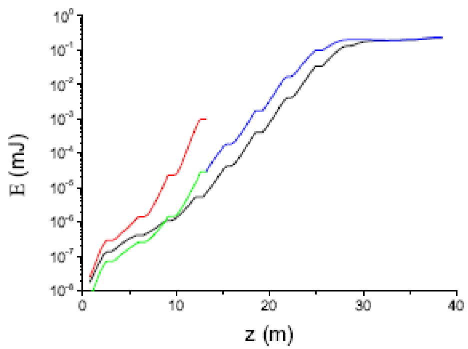


Figure 2: FEL pulse energy versus undulator length. In the first part of the undulator (tuned to the resonance with 39 nm) the first (red) and the third (green) harmonics are shown. The third harmonic continues to get amplified in the second part of the undulator (now as the fundamental) tuned to 13 nm (shown in blue). A reference case of lasing at 13 nm on the fundamental in the whole undulator with constant K-value is shown in black.

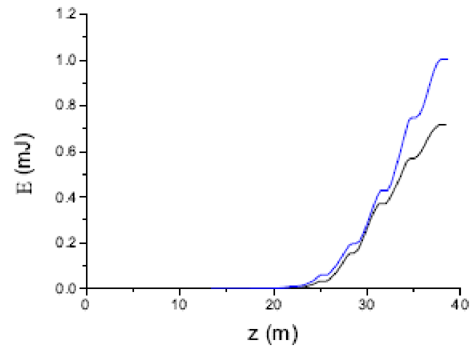


Figure 3: FEL pulse energy versus undulator length when the post-saturation taper is applied. HLSS case is shown in blue, and the SASE case - in black.

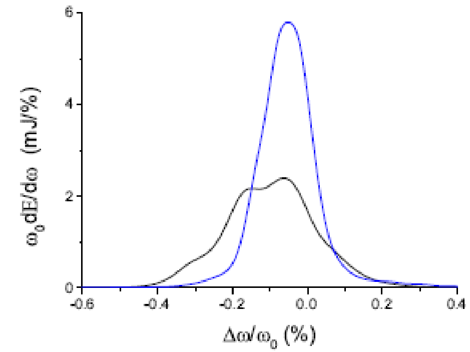


Figure 4: Spectral density of the radiation energy for HLSS FEL configuration (blue) and for SASE FEL (black).

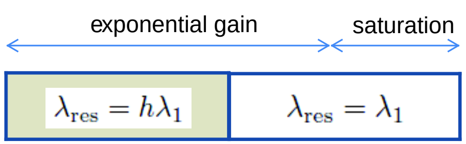
- A gap-tunable planar undulator is divided into two parts such that the first part is tuned to a sub-harmonic of the second part.
- Harmonic lasing occurs in the exponential gain regime in the first part of the undulator,
- In the second part of the undulator the fundamental mode is resonant to the wavelength, previously amplified as the harmonic, and amplification process proceeds to saturation.
- Benefits of HLSS: improvement of the longitudinal coherence, reduction of the spectrum width, and increase of spectral brightness.
- Application of the post-saturation tapering would allow to generate higher peak power than in SASE mode due to an improved longitudinal coherence.

E.A. Schneidmiller and M.V. Yurkov, Recent activities at FLASH and European XFEL, 2016 International Workshop on EUV and Soft X-Ray Sources, Amsterdam, November 7-9, 2016

Harmonic lasing self-seeding (HLSS)

Experiment at FLASH2 on May 1, 2016 (945 MeV, 400 pC, 7 nm):

- Demonstration of harmonic lasing in a high-gain FEL;
- Demonstration of HLSS scheme.



21 nm 7 nm

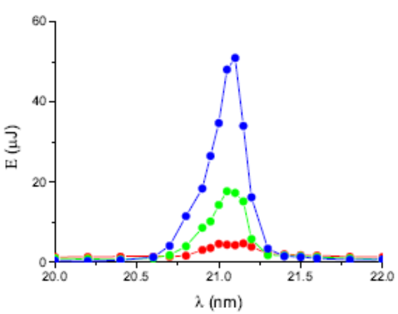


Figure 5: Scan of the resonance wavelength of the first part of the undulator consisting of one undulator section (red), two sections (green), and three sections (blue). Pulse energy is measured after the second part of the undulator tuned to 7 nm.

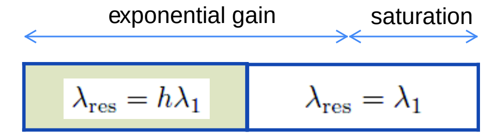
- Initially 10 undulator sections were tuned to the exponential gain regime at 7 nm; the pulse energy was 12 μJ.
- Then the first section was detuned from 7nm (the pulse energy was reduced to about 1 μJ), tuned to the third subharmonic and scanned around 21 nm (red curve).
- Then measurements were repeated with the first two sections, and then with the first three sections (green and blue curves). The effect is essentially resonant.
- Pulse energy at 21 nm wavelength from 3 undulator section was 40 nJ, far away from saturation, thus excluding mechanism of the nonlinear harmonic generation in the first part of the undulator.

E. Schneidmiller and M. Yurkov, Proc. IPAC2016, MOPOW009

Harmonic lasing self-seeding (HLSS)

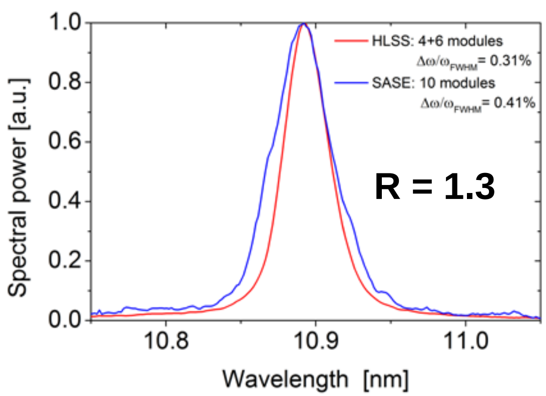
HLSS experiment at FLASH2 on June 6-7, 2016 @ 760 MeV

11 nm: demonstration of spectrum width reduction, increase of spectral brightness, and increase of coherence time.



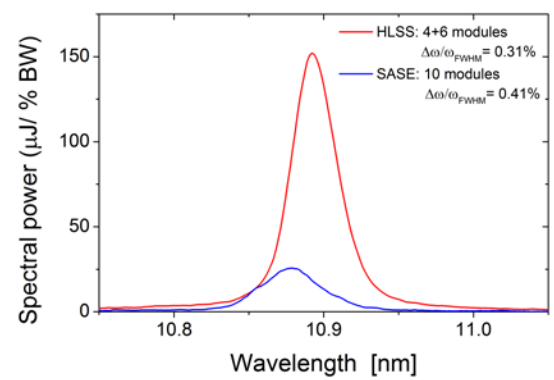
4u x 33 nm   6u x 11 nm

- Initially 10 undulator sections were tuned to the SASE regime at 11 nm; the pulse energy was 11 μJ. Radiation spectra have been measured.
- Then four first undulator modules were tuned to 33 nm, the third subharmonic of 11 nm. Radiation pulse energy at 7 nm was 51 μJ. Background from 33 nm radiation has been measured on the level of 50 nJ, far away from saturation, thus excluding mechanism of the nonlinear harmonic generation in the first part of the undulator.
- Radiation spectra in HLSS scheme have been measured. Reduction of the spectrum width is about of factor of R = 1.3 - less than expected value of about R = 1.7. The reason is chirp in the electron beam.



Expectations: R = 1.7

$$R \simeq h \frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{\rm sat,1}}$$



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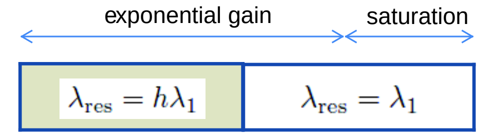
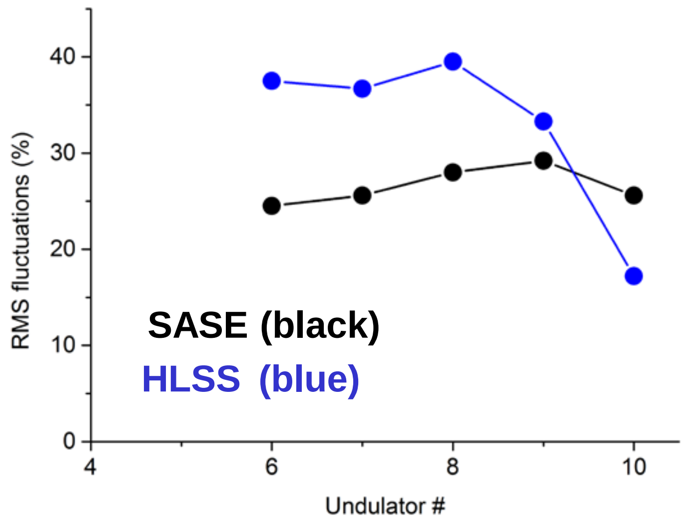
Harmonic lasing self-seeding (HLSS)

Experiment at FLASH2 on June 6-7, 2016 at 11 nm: demonstration of spectrum width reduction, increase of spectral brightness, and increase of coherence time.



4u x 33 nm 6u x 11 nm

Statistical determination of an increase of the coherence time



$$M_l \propto 1/L^{coh}$$

$$M_l = 1/\sigma^2$$

$$\frac{L^{coh}_{HLSS}}{L^{coh}_{SASE}} = \frac{\sigma^2_{HLSS}}{\sigma^2_{SASE}} \simeq 1.8$$

Measured increase of the coherence length is in agreement with theory:

$$R \simeq h \frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{\rm sat,1}} = 0.57\ \mathrm{h} = 1.7$$

E.A. Schneidmiller and M.V. Yurkov, Recent activities at FLASH and European XFEL, 2016 International Workshop on EUV and Soft X-Ray Sources, Amsterdam, November 7-9, 2016

Reverse undulator tapering

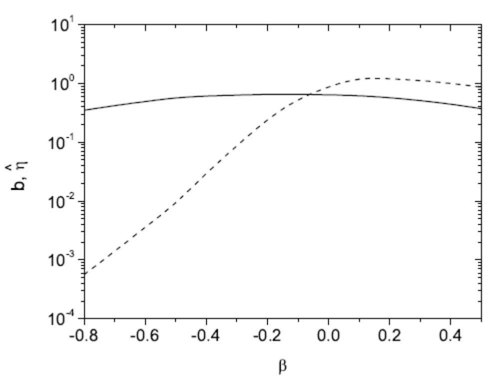
reverse-tapered planar undulator (saturation)

helical afterburner

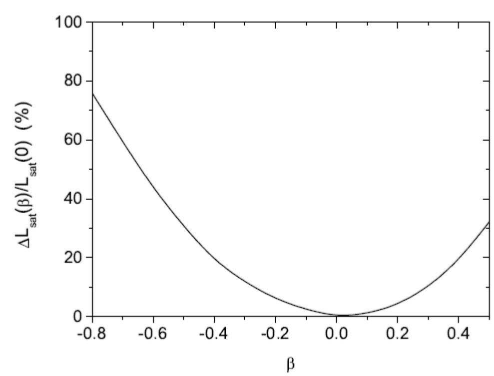
- Fully microbunched electron beam but strongly suppressed radiation power at the exit of reverse-tapered planar undulator
- The beam radiates at full power in the helical afterburner tuned to the resonance

b - bunching factor (0<b<1)

$\hat{\eta} = P/(\rho P_{\mathrm{beam}})$ - normalized power (efficiency)



Bunching and power at saturation

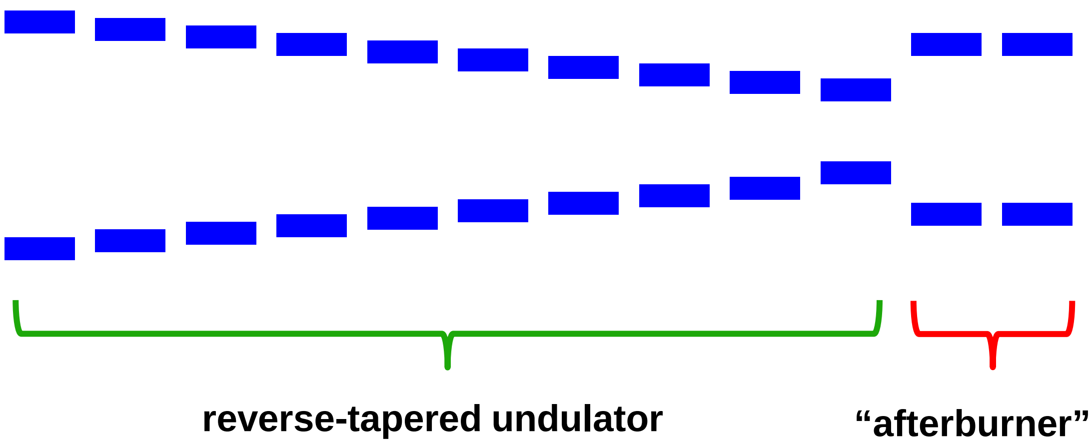


Relative increase of the saturation length

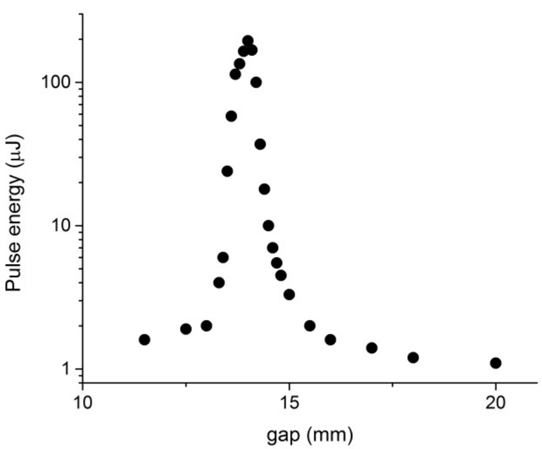
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 110702(2013)16

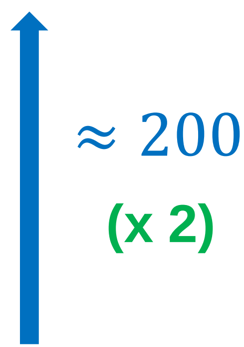
Reverse undulator tapering

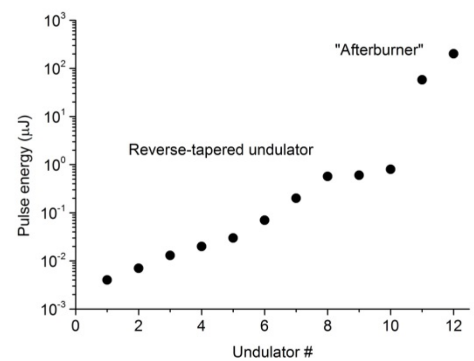
Experiment at FLASH2 on 23.01.2016



- Beam energy 720 MeV,
- Wavelength 17 nm.
- Reverse taper of 10% along 10 undulator segments;
- The gap of the 11th and 12th segments was scanned.
- Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.







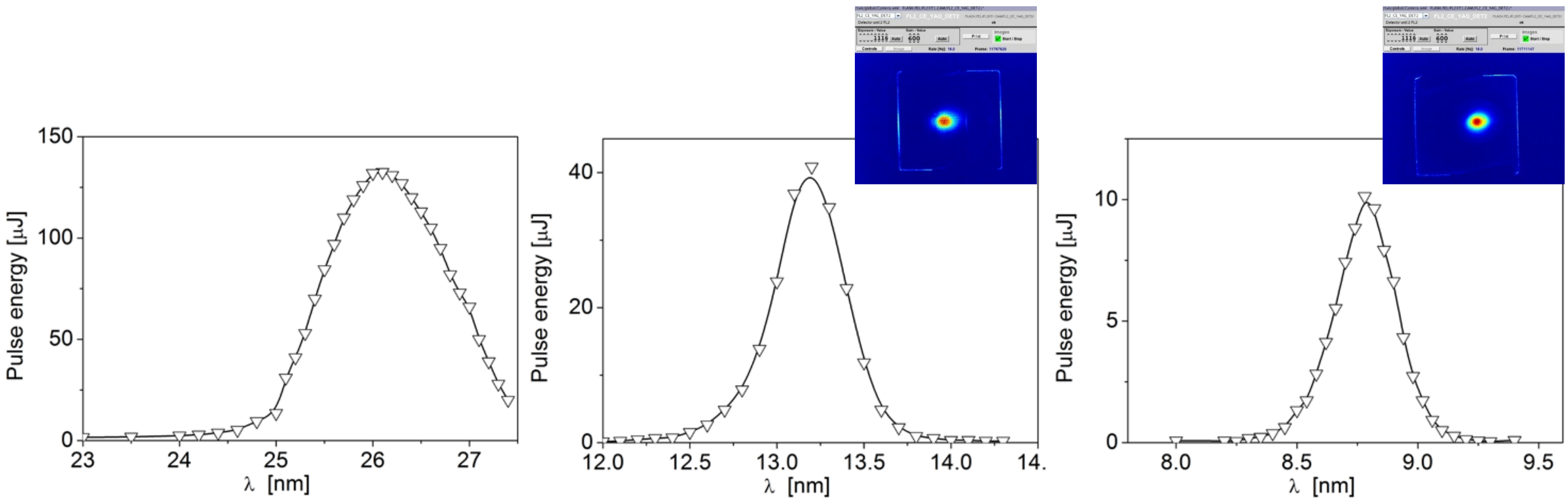
E. Schneidmiller and M. Yurkov, Proc. IPAC2016, MOPOW008

Reverse tapering: higher harmonics

Experiment at FLASH2 on Oct. 10, 2016:

Main undulator: 9 modules, 26.5 nm, -5% taper.

Afterburner: 2 modules, 26.5 nm, 13.2 nm, 8.5 nm



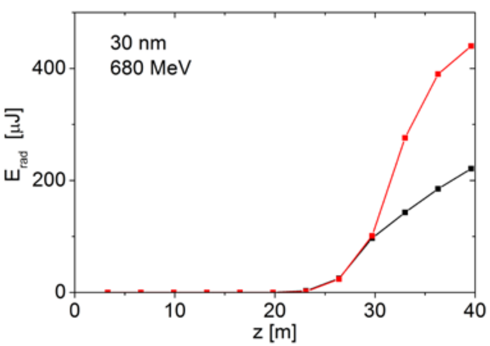
- High contrast of the afterburner radiation with reverse undulator tapering scheme at the fundamental harmonic frequency and harmonics (150 for fundamental).
- Effective operation of an afterburner at the 2^{nd} and the 3^{rd} harmonic with intensities which are much higher (orders of magnitude) than harmonic content of SASE radiation.

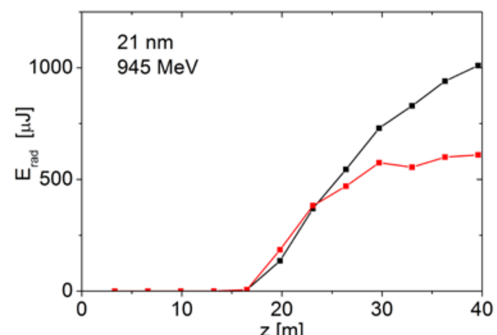
Post-saturation undulator tapering for efficiency increase

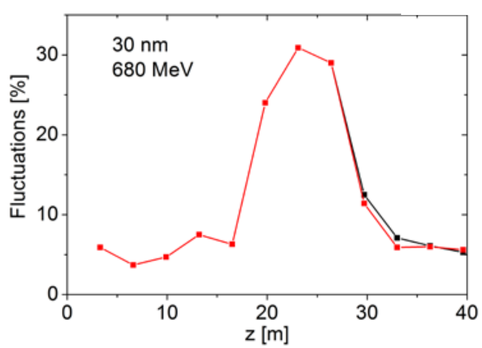
Use of statistical measurements for tuning optimum undulator tapering:

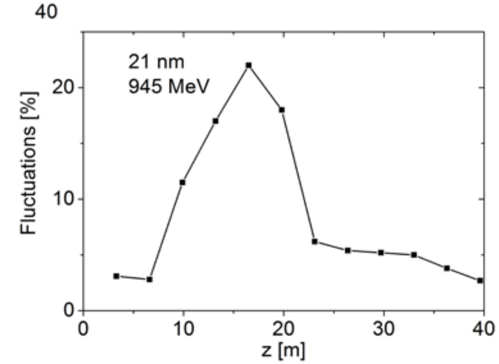
- Optimum conditions of the undulator tapering assume the starting point to be by two field gain lengths before the saturation point (Phys. Rev. ST AB 18, 030705 (2015)) corresponding to the maximum brilliance of the SASE FEL radiation.
- Saturation point on the gain curve is defined by the condition for fluctuations to fall down by a factor of 3 with respect to their maximum value in the end of exponential regime.
- Then quadratic law of tapering is applied (optimal for moderate increase of the extraction efficiency at the initial stage of tapering).

Experimental results from FLASH 2, January-May 2016









Summary

- Commissioning of the European XFEL started.
- Both beamlines, FLASH1 and FLASH2 operate simultaneously for user experiments.
- Innovative FEL developments have been made using variable gap undulator at FLASH2:
  - Frequency doubler scheme demonstrated operation with the wavelength of 3.1 nm at 1230 MeV electron energy.
  - Two color mode of operation has been demonstrated with frequency doubler scheme.
  - Post-saturation undulator tapering demonstrated increase of the radiation pulse energies above 1 mJ.
  - High contrast of the afterburner radiation with reverse undulator tapering scheme has been demonstrated at the fundamental harmonic. Effective operation of an afterburner at the 2^{nd} and the 3^{rd} harmonic has been demonstrated with intensities which are much higher (orders of magnitude) than harmonic content of SASE FEL radiation.
  - Harmonic lasing in the high gain SASE FEL has been demonstrated experimentally for the first time.
  - Harmonic lasing self-seeding scheme has been successfully demonstrated. Significant increase in the spectral brightness has been obtained. Coherence time has been increased by a factor of about 2.

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